SPECIFICATION

METHOD AND APPARATUS TO AUTOMATICALLY DETERMINE TISSUE CANCELLATION PARAMETERS IN X-RAY DUAL ENERGY IMAGING

Background of Invention

[0001]   The preferred embodiments of the present invention relate to medical diagnostic X-ray imaging. In particular, the preferred embodiments of the present invention relate to dual energy decomposition for tissue specific imaging using a look-up table to obtain a range of cancellation parameters.

[0002]   Today, doctors and technicians commonly have access to very sophisticated medical diagnostic X-ray imaging devices. Typically during the operation of an X-ray imaging device, an X-ray source emits X-ray photons under very controlled circumstances. The X-ray photons travel through a region of interest (ROI) of a patient under examination and impinge upon a detector. In the past, X-ray imaging devices employed rudimentary film based detectors. However, recent developments have led to solid state detectors comprised of a grid of discrete detector elements that individually respond to exposure by X-ray photons. Regardless of the detector used, however, the goal remains the same, namely to produce a clear resultant image of preselected structures of interest (e.g., specific types of tissues) within the ROI.

[0003]   There is an inherent difficulty associated with producing a clear resultant image, however. In particular, because the X-ray photons travel through the entire

patient, the image formed on the detector is a superposition of all the anatomic structures through which X-ray photons pass, including the preselected structures of interest. The superposition of anatomic structures is sometimes referred to as "anatomic noise". The effect of anatomic noise on the resultant image is to produce clutter, shadowing, and other obscuring effects that render the resultant image much less intelligible than the ideal clear resultant image.

[0004]   Past attempts to reduce the effects of anatomic noise included, for example, "dual-energy" imaging. When employing dual-energy imaging, a doctor or technician acquired an image at high average X-ray photon energy, and an image at low average X-ray photon energy. Because different internal structures absorb different X-ray photon energies to different extents, it was possible to combine the two resultant images to suppress anatomic noise, according to:

$$SB(x,y) = exp[log\ (H(x,y)) - w\ log\ (L(x,y))],\ (0 < w < 1),$$

where SB is the decomposed image achieved through the log subtraction at a specific cancellation parameter w, H(x,y) is an image obtained at high energy, and L(x,y) is an image obtained at low energy. By varying w, SB becomes a decomposed image of either soft tissue or of bone.

[0005]   However, in the past, users of the previously mentioned decomposition technique had to vary the cancellation parameter, w, manually through trial and error until the resultant image emphasized the soft tissue or bone of interest and de-emphasized the other. The resulting manual variation of the cancellation parameter in the log subtraction equation was time consuming and hindered the workflow in the clinical environment.

[0006]   A need has long existed in the industry for a method and apparatus for dual energy decomposition that addresses the problems noted above and previously experienced.

Summary of Invention

[0007]   In accordance with at least one preferred embodiment, a method is provided to automatically determine a structure cancelled image in a dual energy

decomposition system. A high energy and a low energy level image of internal anatomy formed of at least first and second types of structure are acquired. A gradient mask is computed using an edge cancellation parameter and a gradient threshold. A localization mask is computed from a localization image based on either the low or the high energy image and compared with an intensity threshold automatically selected from a set based upon a selected diagnostic application. A characteristic mask is computed using the gradient mask and localization mask. A first cancellation parameter is evaluated against the characteristic mask, and a second cancellation parameter is computed based upon the first cancellation parameter. In accordance with at least one preferred embodiment, the first or second cancellation parameter is selected from a range in a look-up table determined by an effective kVp used to acquire the high level image and an effective kVp used to acquire the low level image. Hard and soft structure cancelled images are obtained from the first and second energy level images according to a cancellation equation using the first and second cancellation parameters. In accordance with an alternative embodiment, the cancellation equation represents a relationship between the high and low energy images adjusted according to the first or second cancellation parameter.

[0008]   In accordance with at least one alternative embodiment, a gradient mask is generated from a ratio of the high to low energy images where at least one of the images is adjusted based on the first or second cancellation parameter. In one embodiment, the high and low energy level images are compressed before generating the gradient mask. In another embodiment, a gradient image is generated based on the high and low energy image. The gradient image is then compared with a gradient threshold to form the gradient mask.

[0009]   In accordance with at least one preferred embodiment, computing the characteristic mask further comprises creating a gradient image by convolving a Sobel operator with an image based on the low and high energy level images. A predetermined gradient threshold is automatically selected from a set based upon a selected diagnostic application and compared to the gradient image to create the gradient mask.

[0010] In accordance with at least one preferred embodiment, the characteristic mask is computed by comparing pixels of the gradient mask to corresponding pixels of the localization mask and assigning an identifier to the pixel of the characteristic mask if the corresponding pixels of the gradient mask and the localization mask are equal and a different identifier if the pixels are not equal. In an alternative embodiment, a first value is assigned to pixels in the characteristic mask representing one type of structure and a second value is assigned to pixels in the characteristic mask representing a second type of structure.

[0011] In accordance with at least one preferred embodiment, a series of gradient maps are generated utilizing the cancellation equation and high and low energy level images by adjusting the first cancellation parameter to a value having a maximum likelihood of emphasizing the first type of structure. In an alternative embodiment, the gradient maps are further computed using cancellation parameters from a look-up table, and the lowest gradient value and associated cancellation parameter for each pixel location is identified.

[0012] In accordance with at least one preferred embodiment, the cancellation parameter having the maximum likelihood of canceling the first type of structure is identified as the peak of a histogram comprised of the lowest gradient values. In an alternative embodiment, the cancellation parameter is identified by calculating the mean of the cancellation parameters associated with the lowest gradient values derived from the characteristic mask.

Brief Description of Drawings

[0013] Figure 1 illustrates a high level diagram of an X-ray imaging system in accordance with a preferred embodiment of the present invention.

[0014] Figure 2 illustrates a flow-chart of a process to decompose X-ray images in accordance with a preferred embodiment of the present invention.

[0015] Figure 3 illustrates a flow-chart of a method to determine the minimum gradient value at every pixel location of the characteristic mask in accordance with a preferred embodiment of the present invention.

[0016]   Figure 4 illustrates a characteristic mask in accordance with a preferred embodiment of the present invention.

[0017]   Figure 5 illustrates a histogram of the quantity of w parameters with the lowest gradient values in accordance with a preferred embodiment of the present invention.

[0018]   Figure 6 illustrates the soft structure decomposed image in accordance with a preferred embodiment of the present invention.

[0019]   Figure 7 illustrates the hard structure decomposed image in accordance with a preferred embodiment of the present invention.

[0020]   The foregoing summary, as well as the following detailed description of the preferred embodiments of the present invention, will be better understood when read in conjunction with the appended drawings. For the purpose of illustrating the preferred embodiments of the present invention, there is shown in the drawings, embodiments which are presently preferred. It should be understood, however, that the present invention is not limited to the arrangements and instrumentality shown in the attached drawings.

Detailed Description

[0021]   With initial reference to Figure 1, the figure illustrates an X-ray imaging system 100. The imaging system 100 includes an X-ray source 102 and a collimator 104 which subject structure under examination 106 to X-ray photons. By way of example, the X-ray source 102 may be an X-ray tube, and the structure under examination 106 may be a human patient, test phantom or other inanimate object under test.

[0022]

        The X-ray imaging system 100 also includes an image sensor 108, such as a flat panel solid state detector, coupled to a processing circuit 110. The processing circuit 110 (e.g., a microcontroller, microprocessor, custom ASIC, or the like) couples to a memory 112 and a display 114. The memory 112 (e.g., including one or more of a hard disk, floppy disk, CDROM, EPROM, and the like) stores a high

energy level image 116 (e.g., an image read out from the image sensor 108 after 110-140 kVp exposure) and a low energy level image 118 (e.g., an image read out after 60-90 kVp exposure). The memory 112 also stores instructions for execution and a look-up table 122 of parameters used by the processing circuit 110, as explained below, to cancel certain types of structure in the images 116 and 118, such as hard structure (bone) or soft structure (tissue). One or more structure cancelled images 120 are thereby produced for display.

[0023]   The processing circuit 110 uses a cancellation technique to decompose spatially registered images from the structure under examination 106 into constituent materials (e.g., bone and soft tissue in chest X-ray images). For example, a chest X-ray image may be decomposed to create one image representing hard structure, such as bone, and one image representing soft structure, such as lung.

[0024]   Figure 2 illustrates one exemplary processing sequence carried out by the x-ray imaging system 100. At step 200, a high energy level image 116 and a low energy level image 118 are acquired and stored in memory 112. The images 116 and 118 contain both hard and soft structure. In at least one preferred embodiment, the high energy level image 116 and the low energy level image 118 are reduced to a smaller matrix size. This reduction may be accomplished by neighborhood averaging and the like.

[0025]

At step 204, the processing circuit 110 determines a parameter that is likely to extract one type of structure, mainly either soft or hard structure. In at least one preferred embodiment, the parameter may be a derived from a look-up table (LUT) 122, also stored in memory 112, as shown below in Table 1:

[t1]

TABLE 1

L 90				0.66 [0.55,0.75]
L 80		0.65 [0.55,0.75]	0.6 [0.5-0.7]	0.55 [0.45,0.65]
L 70	0.57 [0.45,0.65]	0.53 [0.43,0.63]	0.5 [0.4,0.6]	$w_c = 0.48$ w-range = [0.38, 0.58]
L 60	0.46 [0.35,0.55]	0.43 [0.33,0.53]	0.41 [0.31,0.51]	0.38 [0.28,0.48]
	H 110	H 120	H 130	H 140

[0026]   The low energy kVp levels are illustrated in the left column and the high energy kVp levels are illustrated in the bottom row. The kVp levels represent the effective kVp to the structure under examination 106, which may vary from the kVp level of the X-ray source 102. The variance may be due to the use of one or more filters used to modulate the kVp. The filter may be comprised of copper, aluminum, or other material or combination of materials and may be located near the collimator 104.

[0027]   Table 1 is further comprised of parameters determined based on humanoid phantom studies or based on human patients at different kVp levels for high energy level images 116 and low energy level images 118. The numbers in Table 1 represent the parameter, w_c, that has a likelihood of canceling one of the types of structure (hereafter sometimes referred to as the cancellation parameter) and a range of parameters, w-range, that will be utilized to determine the parameter that may best cancel the second type of structure (hereafter sometimes referred to as the cancellation range). For example, if a low energy level image 118 is acquired with an effective kVp of 60 and a high energy level image 116 is acquired with an effective kVp of 110, Table 1 may be utilized to find the cancellation parameter w_c = 0.46 and the cancellation range w-range = [0.35,0.55].

[0028]

At step 204, the processing circuit 110 computes a gradient mask. First, in a preferred embodiment, an edge cancellation parameter w_{edge} is computed using the cancellation parameter w_c from Table 1 in the following equation:

$$w_{edge} = (1 + w_c)/2.$$

Continuing the above example, the value of the cancellation parameter w_c is 0.46, thus the edge cancellation parameter w_{edge} = 0.73. In an alternate embodiment, a predetermined cancellation parameter found to work well to extract one type of structure may be used. The predetermined parameter may be dependent upon the type of image being acquired. Next, in a preferred embodiment, the processing circuit 110 processes the edge cancellation parameter w_{edge}, the reduced high energy level image and the reduced low energy level image according to Equation 1 below:

$$I(x,y) = I_{HIGH}(x,y) / (I_{LOW}(x,y))^w \qquad \text{(Equation 1)}$$

where w is w_{edge}, and $I_{HIGH}(x,y)$ and $I_{LOW}(x,y)$ are the pixels' intensity values of the reduced high and low energy level images. Equation 1 is much faster than the log subtraction equation previously utilized, and thus is an improved method of decomposing images.

[0029]   The processing circuit 110 then computes a gradient using the result of Equation 1, decomposed image I(x,y). In a preferred embodiment, the gradients may be obtained by convolving a Sobel operator with decomposed image I(x,y). Next, the gradients are compared to a gradient threshold. The gradient threshold is a fixed value that is set based upon the application. In an embodiment of the present invention, the gradient threshold may be picked from a set of values based upon the application, such as chest, c-spine, and lumbar spine by way of example only. The gradient mask is created by assigning a first identifier (e.g. such as 1) to any pixel greater than the gradient threshold and a second identifier (e.g. such as 0) to any pixel less than the gradient threshold. The processing circuit 110 may store the gradient threshold in memory 112.

[0030]

At step 206, the processing circuit 110 creates a characteristic mask by computing a localization mask to identify the soft structure and comparing the localization mask to the gradient mask. To compute the localization mask, the low

energy level image 118 is compared with an intensity threshold. In a preferred embodiment, the intensity threshold is based upon the average or mean intensity of the image. In an alternative embodiment, the intensity threshold is a fixed value based upon the application. The localization mask is created by assigning a first identifier (e.g. 1) to any pixel greater than the intensity threshold and a second identifier (e.g. 0) to any pixel less than the intensity threshold. The processing circuit 110 may store the localization mask in memory 112.

[0031]   Next, processing circuit 110 computes a characteristic mask. Figure 4 illustrates a characteristic mask 124. In a preferred embodiment of the present invention, the characteristic mask 124 is a binary mask in which the pixels representing the hard structure, or bone, are white, and the pixels representing the soft structure, or lungs, including the ribs, are black. The characteristic mask is computed by comparing the pixels of the gradient mask to the corresponding pixels of the localization mask. For pixel locations that contain the first identifier (e.g. 1) in both the gradient mask and the localization mask, the corresponding pixel location of the characteristic mask is assigned the second identifier (e.g. 0). For pixel locations that contain the first identifier (e.g. 1) in either the gradient mask or the localization mask but not both, the corresponding pixel location of the characteristic mask 124 is assigned the first identifier (e.g. 1). The characteristic mask 124 may be stored in memory 112.

[0032]   At step 208, the processing circuit 110 identifies the minimum gradient at every pixel location of the characteristic mask containing the first identifier (e.g. 1). In a preferred embodiment, cancellation parameters from the LUT 122 and the high energy level image 116 and the low energy level image 118 are utilized in Equation 1 to obtain the decomposed image I(x,y). Continuing with the above example, the cancellation range w-range used in Equation 1 will be 0.35 0.55. Equation 1 is calculated at each pixel location corresponding to the pixel locations of the characteristic mask 124 containing the first identifier (e.g. 1). In one preferred embodiment, the first value of cancellation parameter w used in Equation 1 is 0.55. In an alternative embodiment, the first value of cancellation parameter w used in Equation 1 is 0.35.

[0033]   Next, the gradient is computed for each decomposed image $I(x,y)$ of Equation 1. In a preferred embodiment, the decomposed image $I(x,y)$ is convolved with a Sobel operator to obtain the gradient at each point (x,y) of interest from the characteristic mask 124. The gradients and corresponding cancellation parameter w are recorded. In a preferred embodiment, each gradient and corresponding cancellation parameter w are stored in memory 112. In an alternative embodiment, the gradient and corresponding cancellation parameter w are stored as an image. The next set of gradients are now computed from decomposed image $I(x,y)$ using the next parameter in the cancellation range w-range in Equation 1. In a preferred embodiment, the value of the cancellation parameter w is varied (e.g. increased or decreased) by .01, and the gradient is calculated at each point of interest in the new decomposed image $I(x,y)$. The process is repeated for every cancellation parameter w over the cancellation range w-range. In an alternative embodiment, the cancellation parameter w is varied over the range and the gradients are calculated at predetermined intervals. The gradients at each pixel location are then compared to determine the lowest gradient and corresponding cancellation parameter w at each pixel (x,y) location.

[0034]   Figure 3 illustrates a preferred embodiment of the method the processing circuit 110 utilizes to determine the minimum gradient at every pixel location of the characteristic mask 124 containing the first identifier (e.g. 1). First, at step 300, the decomposed image $I(x,y)$ is computed utilizing the largest parameter in the cancellation range w-range (hereafter sometimes referred to as w_{MEMORY}), the high energy level image 116 and the low energy level image 118 in Equation 1. Continuing with the above example, the value of w_{MEMORY} is .55. Next, at step 302, the gradients (hereafter sometimes referred to as gradients$_{MEMORY}$) are calculated. This may be accomplished by convolving a Sobel operator with the decomposed image $I(x,y)$. The gradients$_{MEMORY}$ and w_{MEMORY} are then saved in memory 112 at step 304.

[0035]   At step 306, the next value of cancellation range w-range (hereafter sometimes referred to as w_{SECOND}) to be used in Equation 1 is computed. As illustrated in Figure 3 step 306, .01 is subtracted from w_{MEMORY} ($w_{SECOND} = w_{MEMORY} -$

.01). Continuing with the above example, the parameter w_{SECOND} is .54.

[0036]   Step 308 makes sure that the value of w_{SECOND} is within the cancellation range w-range. If w_{SECOND} is less than the cancellation range w-range, control passes to step 310 and the processing circuit 110 returns to step 210 of Figure 2. If w_{SECOND} is not less than the cancellation range w-range, control passes to step 312.

[0037]   At step 312, w_{SECOND} is utilized with the high energy level image 116 and the low energy level image 118 in Equation 1 to compute decomposed image I(x,y). Next, at step 314, the gradients (hereafter sometimes referred to as $gradients_{SECOND}$) are calculated. Again, this may be accomplished by convolving a Sobel operator with the decomposed image I(x,y). At step 316, the processing circuit 110 identifies the first pixel (x,y) to be compared. The step 318 asks: Is $gradients_{MEMORY} < gradients_{SECOND}$ at pixel (x,y)? If the answer to the question is no, control passes to step 320 and parameters $gradients_{SECOND}$ and w_{SECOND} are stored in memory 112 and parameters $gradients_{MEMORY}$ and w_{MEMORY} are discarded. Parameter $gradients_{MEMORY}$ is assigned the value of $gradients_{SECOND}$, and parameter w_{MEMORY} is assigned the value of w_{SECOND}. If the answer to the question is yes, parameters $gradients_{MEMORY}$ and w_{MEMORY} are stored in memory 112.

[0038]   Next, step 322 asks: Is pixel (x,y) the last pixel location? If the answer is no, control passes to step 324 where the processing circuit 110 instructs to continue to the next pixel (x,y) location and return to step 318 to continue identifying the lowest gradients. If the answer is yes, the lowest gradient and corresponding cancellation parameter for each pixel has been stored in memory 112. Next, step 326 computes the next cancellation range w-range parameter by decreasing w_{SECOND} by .01. Control passes to step 308, where the method continues to evaluate the gradients for every parameter of the cancellation range w-range.

[0039]   In an alternative embodiment, the gradients are computed for each parameter in the cancellation parameter w-range and stored in memory 112. After all of the gradients have been computed, the gradients are compared at each pixel (x,y)

location to identify the minimum gradient and corresponding w parameter.

[0040]   At step 210, the processing circuit 110 determines the initial cancellation parameter having the maximum likelihood of emphasizing the first type of structure. First, the cancellation parameters w identified above are used to calculate the total number of occurrences of each cancellation parameter w at the minimum gradient values, and the cancellation parameter w with the highest number of occurrences is identified as the maximum likelihood cancellation parameter w_{ML}. In a preferred embodiment of the present invention, the cancellation parameters w are used to create a histogram 126, as illustrated in Figure 5. The number of occurrences of the cancellation parameter w are represented on the vertical axis and the corresponding cancellation parameters w are represented on the horizontal axis of the histogram 126. The maximum likelihood cancellation parameter w_{ML} having the maximum likelihood of canceling the first type of structure is identified as the peak of the histogram 126. In an alternative embodiment, the mean or average value of the cancellation parameters w may be used to identify the maximum likelihood cancellation parameter w_{ML}.

[0041]   At step 212, the processing circuit 110 calculates the parameter with the maximum likelihood of canceling the first type of structure w_s and the parameter with the maximum likelihood of canceling the second type of structure w_b. First, the maximum likelihood parameter w_{ML} identified in block 210 is evaluated. It is possible that an error may have occurred during the acquisition of the high energy level image 116 or the low energy level image 118, or during the subsequent processing of the image which may cause maximum likelihood parameter w_{ML} to be invalid. In a preferred embodiment, the histogram 126 is evaluated to determine whether the peak of the histogram 126 is at either extreme edge of the cancellation range w-range. If the peak is at either extreme edge of the cancellation range w-range, then the parameter with the maximum likelihood of canceling the first type of structure w_s is equal to the cancellation parameter w_c (e.g. $w_s = w_c$). If the peak of the histogram 126 is in the central area of the histogram 126, then the parameter with the maximum likelihood of canceling the

first type of structure w_s is equal to the maximum likelihood cancellation parameter w_{ML} (e.g. $w_s = w_{ML}$) Next, the parameter with the maximum likelihood of canceling the second type of structure w_b is calculated using the parameter with the maximum likelihood of canceling the first type of structure w_s in the following linear relationship:

$$w_b = a(w_s) + b,$$

where a and b are constants. In a preferred embodiment, a = b = 0.5.

[0042]   At step 214, the processing circuit 110 determines whether to recalculate the parameter with the maximum likelihood of canceling the first type of structure w_s and the parameter with the maximum likelihood of canceling the second type of structure w_b. In an embodiment of the present invention, the decision is made to refine the edge cancellation parameter w_{edge} and recalculate the parameter with the maximum likelihood of canceling the first type of structure w_s and parameter with the maximum likelihood of canceling the second type of structure w_b. Control passes to step 216, where the processing circuit assigns the edge cancellation parameter w_{edge} the value of the parameter with the maximum likelihood of canceling the second type of structure w_b ($w_{edge} = w_b$). Next, the method returns to step 204 and repeats the steps described above. If the value of the maximum likelihood cancellation parameter w_{ML} at step 210 does not change, there is no need to further refine the maximum likelihood cancellation parameter w_{edge}. In a preferred embodiment, step 214 is optional and the parameters with the maximum likelihood of canceling the first type of structure w_s and second type of structure w_b are not recalculated. Instead, control passes to step 218.

[0043]

At step 218, the processing circuit 110 creates the decomposed images 128 and 130. The parameter with the maximum likelihood of canceling the first type of structure w_s and second type of structure w_b are used in Equation 1 with the original high energy level image 116 and low energy level image 118. Using the value of the parameter with the maximum likelihood of canceling the first type of structure w_s in Equation 1 as shown below:

$$I_s(x,y) = I_{HIGH}(x,y) / (I_{LOW}(x,y))^{w_s}$$

will result in an image of soft structure 128, as illustrated in Figure 6. Using the parameter with the maximum likelihood of canceling the second type of structure w_b in Equation 1 as shown below:

$$I_b(x,y) = I_{HIGH}(x,y) / (I_{LOW}(x,y))^{w_b}$$

will result in an image of hard structure 130, as illustrated in Figure 7.

[0044]   Having the values of the cancellation parameter w_c and the cancellation range w-range empirically determined and available in the LUT 122 can improve the performance of image decomposition. As the method illustrated in Figure 2 utilizes the predetermined parameters, such as cancellation parameter w_c, cancellation range w-range, gradient threshold, intensity threshold and the like, input from the operator is not necessary and the time required to complete the calculations is reduced. The method tests the cancellation range w-range and determines the maximum likelihood cancellation parameter w_{ML} through comparison of the gradient values at each pixel (x,y). The method is not subject to possible operator biases, thus, the parameters with the maximum likelihood of canceling the first type of structure w_s and second type of structure w_b determined by the method will be the parameters that provides the best cancellation of the chosen structure.

[0045]   While the invention has been described with reference to a preferred embodiment, those skilled in the art will understand that various changes may be made and equivalents may be substituted without departing from the scope of the invention. In addition, many modifications may be made to adapt a particular step, structure, or material to the teachings of the invention without departing from its scope. Therefore, it is intended that the invention not be limited to the particular embodiment disclosed, but that the invention will include all embodiments falling within the scope of the appended claims.